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PRECISION WINDING OF CYLINDRICAL COMPOSITES WITH SHAPED GLASS FILAMENTS

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by Richard A. Humphrey

Prepared by
DeBELL & RICHARDSON, INC.
Hazardville, Conn.
for

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PRECISION WINDING OF CYLINDRICAL COMPOSITES WITH SHAPED GLASS FILAMENTS

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FOREWORD

This is Part I of the final report on Contract NASw-1100, "Hollow Multipartitioned Ceramic Structures." It describes a continuation of work done under Contract NASw-672, same title, whose final report issued as NASA CR-142. Part II, NASA CR-518, "Initiation of Failure Mechanisms in Glass-Resin Composites" by William J. Eakins is being issued concurrently.

ABSTRACT

During the continuation of the first year's effort on forming shaped and hollow glass filaments, the process was refined. Precision windings were made to obtain close packing from rectangular microtape, both solid and hollow, while hollow hexagonal fiber was wound into a micro-honeycomb.

Substantial mechanical properties data were developed on 2.3" diameter tubes precision wound from solid microtape into 90% by volume glass structures. These displayed no room temperature permeability to water and modulus of elasticity values the same as the glass; namely, 10×10^6 psi. Axial strengths of the tubes with only circumferential windings were as high as 25,000 psi.

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INTRODUCTION and SUMMARY

The statement of work comprises a concise expression of the objectives of this contract.

A. Investigate the feasibility of winding resin-wet filaments and tapes on a mandrel in a close uniform spacing arrangement.

B. Form multiple filament and tape structures.

C. Investigate methods of forming complex objects with the new cross section filaments formed under "B" above.

D. Continue to investigate the failure initiation mechanism in glass-resin composites.

Major advances were made in both "A" and "D" above while some progress was made in "B" and "C".

NASW-1100 is a continuation of the original contract NASw-672. The first year's effort, described in the final report and issued as NASA CR-142 (1), was a broad program to explore the capabilities of the preform attenuation process in the forming of a vast number of different shaped cross section glass fibers. The second year's effort, described in this report, was a program of refinement to get some selected shaped filaments into structures in precise placement in order to determine properties of structures made from shaped filaments.

The following is a list of the second year's accomplishments:

1. Designed and installed new improved preform feeding mechanism.
2. Demonstrated feasibility of preform attenuation technique for the drawing of organic polymers in solid and hollow round filaments as well as simple shaped filaments.
3. Refined shaped glass filament forming technique to yield shaped filament which maintains constant dimensions over long lengths.
4. Determined the variables requiring control to; (a) make constant dimension shaped filament, and (b) precision wind such a filament.
5. Procured new lathe with precision feed screw. Designed and installed modifications to make lathe into precision tube winder.
6. Utilized new preform feeder and new lathe winder to make tubular structures from microtape.
7. Obtained mechanical properties on tubes precision wound from solid and hollow microtape, determining circumferential and axial modulus and strength properties.
8. Made precision windings of hollow, hexagonal filaments and determined physical properties.
9. Shipped shaped glass filaments to other investigators.

10. Studied the micromechanics of resin block and single microtape embedments which provided an opportunity to analyze internal and external stress loading and failure analyses in both circular filament wound and microtape wound materials. The effect of external loading of castings on their water absorption was also examined. The results of this study are presented in Part II of this final report.

EQUIPMENT

The designing, procuring, modifying and installing of special equipment to form and precisely wind shaped filaments during this year has contributed a great deal toward the refining of the process for making structures from shaped filaments.

Precision Lathe Winder

The new winder has been made by modifying a Clausing 10" x 36" lathe. Instead of the usual lathe head stock, the mandrel is driven by a DC variable speed motor which is mounted on a platform along with the lathe tail stock. This platform, fabricated from two 4" aluminum I-beams and a 3/8" thick aluminum plate, is anchored to the lathe saddle carriage. The cross feed is not used. A second identical DC motor drives the carriage through the change gears and the feed screw. Both of these motors are driven from a common control so they will run at the same speed. At both the right and left ends of the traverse, a limit switch is located which reverses the direction of rotation of only the traverse motor with the mandrel drive motor continuing in the

same direction. In this way, layer after layer of shaped filament can be wound onto the mandrel without stopping.

Figures 1 and 2, which may be unfolded to permit ready comparison with the details in the text, are views of this winder. In Figure 1, from left to right, the operator has within reach the winder controls, the mandrel tachometer, the lathe apron controls; and in the upper center, the filament guides and microscope monitor. At the upper right center are the feeder controls and, at the far right, the furnace temperature controls and precision portable potentiometer for chamber temperature monitoring. Figure 2, the rear view of the lathe winder, shows the microscope at the top for monitoring filament size, immediately below which the resin is first applied. The rigid guide support, fabricated from square tubing and fastened to the lathe bed, holds the floating guide and wiper assembly. Additional resin may be added at this final guide. The mandrel drive motor and tachometer are in the upper foreground. The fabricated mandrel support platform is fastened to the lathe saddle carriage. On the platform are mounted the tail stock at the far end and the mandrel drive motor at the near end. The traversing motor, in the foreground, drives the saddle through the change gears and feed screw. Adjustable limit switches are mounted at the back on rails fastened to the lathe bed. Across the back of the lathe pedestals, below, can be seen the automatic controls for the two winder motors.

The precision winder is designed to operate with a broad range of mandrel sizes, speeds and traverse rates to utilize many different filament sizes and shapes. The following list illustrates this versatility.

Modified Lathe Winder Specifications

Maximum length of traverse	36"
Normal maximum wound structure length	30"
Maximum wound structure diameter	10"
Mandrel diameters available:	
for nominal 2" pipe O. D.	2.295"
for NOL ring tubes	5.750"
for making 28" square flat laminates	8.910"
Mandrel speed; continuously adjustable	50 to 550 RPM
Traverse spacings	
Fine, in 26 increments	.00447" to .0313"
Coarse, in 26 increments	.0358" to .250"

By moving the mandrel back and forth beneath a fixed guide, the angle and length of the filament from the furnace across the microscope and the guide remains constant at all times. Monitoring the size of the filament with the microscope permits the operator to adjust the speed of the mandrel, and simultaneously the traverse rate, maintaining the proper filament size to be accommodated by the chosen traverse gap.

Preform Feeder

The forming of a constant size filament demands that the preform of uniform dimensions is fed into the furnace at a constant rate and that the filament is withdrawn at a constant speed. Therefore, the new, more rigid, mechanical feeder with a capacity to handle greater length preforms was designed and build to provide the requisite constant feed speed.

The mechanical preform feeder is a versatile precision unit. It is powered by two different motors with the slow motor normally being the feed power supply and the fast motor being used for preliminary positioning as well as the installation of the new preform. The use of two separate drive trains permits the operator to go through operations like installing a new preform without disturbing the feed setting. The duplicate pushbutton stations, both upstairs and down, provide "slow feed down", "slow feed up", "stop", "fast feed up" and "fast feed down". In addition to each of these pushbutton control operations, the speed control head for each of the Graham Transmissions is extended down to the vicinity of the operator's position on the first floor to permit exact speed adjustment on each of these two motor drives.

Preform Feeder Capabilities

Maximum Preform Length: 68"

Rates of Travel:

Feed - 0 to 1.25"/min.

Set Up - 0 to 30"/min.

Because the limit switches open both the circuit to the magnetic clutch and the operating motor, preform motion is stopped instantaneously even though the drive motor must coast to a stop. This feeder has lived up to all design expectations having profited by the shortcomings of earlier feeder designs used in these laboratories. One helpful addition to this unit would be a simple indicating device located in the operator's position to tell him what usable length of preform still remains at any time.

Furnace

The furnace has been located on the second floor at a substantially higher level than in earlier applications. It was learned that the final forming of such large filaments as, for example, microtape may not be completed until the filament has reached a point well below the furnace, possibly as far as one foot. By maintaining sufficient distance, the graphite guides necessary in the vicinity of the microscope do absolutely no reshaping of the fiber at that point. Secondly, the filament is cool enough at the first resin application guide to prevent overheating the resin.

One recent improvement in furnace design for the work with shaped glass filament has been the incorporation of a thick-walled stainless steel chamber running vertically through the furnace standing about 2" above the furnace and as much as 4" below the furnace. This chamber serves several functions such as the control of drafts through the critical forming region and the smoothing of the temperature gradient in a vertical direction within

the furnace. In the case of a wide, thin cross section, such as the microtape being used at the present time as a model material for precision winding studies, a wide thin rectangular chamber has worked well. This chamber of 1/8" thick stainless steel is about 1/2" wider than the preform on each edge and has a total thickness of approximately 1/2" giving about 1/4" between each face of the preform and the inside of the steel chamber. A thermocouple is welded directly to the outside face of the stainless steel chamber to assist in setting the automatic controller at the proper temperature. From earlier experience on shaped filaments, it is well-known that the furnace temperature has a profound effect on the cross sectional shape of the filament. Therefore, a null balance, digital set point controller provides information for the silicon control rectifier unit which yields a furnace temperature constant within approximately $\pm 1^{\circ}F$.

Furnace and Feeder Assembly

Figures 3 and 4 are views on the second floor of the furnace, feeder and feeder control boxes. The side view, Figure 3, shows how the insulating fire brick furnace, mounted on vibration isolators, is oriented so the width of the preform is parallel to the mandrel on the lathe downstairs. In the background on the wall are the contactors which control magnetic clutches connecting the slow feed motor or the fast set-up motor to the feeder as well as controlling the direction of rotation of the operating motor. These are controlled by the pushbutton station at the left, a duplicate of that in the

operator's position on the lower floor. Against the side wall can be seen the feeder guide rods between which is the long screw that drives the feeder yoke. The reflection from a long, three inch wide strip of glass can be seen entering the top of the furnace through some graphite guide blocks.

The front view of the second floor assembly, Figure 4, was made with the yoke and a preform attached lowered to where it would be if it were approaching the end of a run on that preform. Close to the bottom of the furnace chamber the ends of the two silicon carbide heating elements extend out to where the electrical straps are connected. The two drive motors can be seen beneath and to each side of the furnace. Each of them drives through a variable speed Graham Transmission, thence a magnetic clutch, one of which can be seen directly beneath the near corner of the furnace. Thus either motor can be coupled through a right angle drive to the long screw, between the guide rods, that drives the yoke by means of a split nut. The lower limit switch is apparent about 9" below the yoke. This switch stops the yoke and the preform in the feed direction at the end of a run while an upper limit switch stops the yoke at a preset level to facilitate loading a new preform. The motor on the lower left is the slow feed motor which is of a synchronous induction type to maintain a constant feed rate. The power transformer for the furnace is out of the picture to the right, located on the second floor to keep the high current leads to a minimum length.

Typical Forming and Winding Procedure

After preheating the furnace, a preform is attached to the feeder yoke. The preform is then lowered between graphite guides on top of the chamber far enough into the furnace that a small amount of the preform can act as a weight below the hot zone to attenuate the preform as it softens. The operator then descends to the first floor and when the bottom of the preform appears below the chamber, it is grasped and pulled downward and manual drawing is continued until a small enough filament is formed so it can be threaded across the microscope guides. The coarse filament is then attached to the end of the mandrel where the excess material can accumulate and the mandrel is started. Shortly thereafter, the preform feed motor is also started and while the filament is plied onto the excess end of the mandrel, the operator observes the filament size through the microscope. He has the possibility of changing the feed speed of the preform and/or the mandrel speed in order to adjust the filament size. Normally the feed speed has been previously established and only the mandrel speed is adjusted. When the proper filament size has been achieved, resin flow is started and the filament is transferred from the temporary traverse guide to the fixed guide for normal filament winding. At the same time, carriage motion is started by pulling up the lever on the apron which closes the split nut onto the feed screw of the lathe. Theoretically, the winding of a tube on the mandrel should be automatic from this point on. Actually the operator must make frequent minor speed adjustments to compensate for filament size changes. As the diameter of the structure being

formed increases, the mandrel speed must be lowered to maintain constant drawing speed. He must also make sure that the resin flow is continuous. Still another job is that of keeping the rubber wipers immediately beneath the fixed guide at the proper angle and pressure to assist in proper filament placement.

The design and location of the guides as well as the wipers is most important towards the forming of a well-packed filament wound structure. The viscosity and surface tension of the resin play an important role in filament placement and the elimination of entrapped air. The cross sectional shape of the filament contributes to the glass content of the finished structure. Should a microtape filament have large edge beads, the structure is bound to have thick resin layers. Should any variation in traverse speed appear for any reason, this results in a non-uniform structure. These and many other factors must be controlled simultaneously to yield optimum structures.

DISCUSSION

In order to make precision wound structures from shaped glass fibers, it is necessary to first produce the chosen cross section filament in continuous lengths of constant cross sectional shape and dimensions. Secondly, the filament must be wound with precision so it will be placed in proper juxtaposition with those windings already in place and those to be wound after it.

The winding problem is further complicated because some shaped fibers, to take full advantage of their shape, can only be wound in one direction. For example, a hexagonal fiber cannot be traversed back and forth in first a right-hand and then a left-hand helix because the crossovers would prevent the perfect packing possible with a hexagonal fiber. On the other hand, a filament with a flat, wide cross section, such as microtape, can be wound continuously in edge-to-edge fashion for layer after layer since a layer which has already been wound presents a perfectly smooth cylindrical surface and causes no interference when a right-hand helix is wound over a left-hand one and vice versa.

Microtape

As a model material to investigate in depth the problems of precision winding, it was decided to use microtape. This flat thin glass filament called microtape was being developed concurrently for NASA Lewis Research Center, Contract No. NAS 3-3647, with the objective of winding it into low permeability structures. A certain amount of experience had been gained in forming microtape and making precision wound structures from it.

A great deal of experience had been gained using the 0.0005" x 0.020" microtape so this size was used at the beginning of this winding study. Even with all the improved equipment and the accumulated fiber forming and precision winding experience, the small microtape was difficult to wind into 100% perfect specimens.

As an example, one of the research specimens required for NASA Lewis is a 0.040" wall tube, 30" long and 2.3" I.D. To wind a perfect specimen with the 0.020" wide microtape requires the drawing of a continuous length of filament over 11 miles long whose width does not vary more than ±0.0005" and necessitates placement in the structure to the same tolerance. By microscope monitoring, the mandrel speed can be adjusted to compensate for gradual width changes; however, sudden fluctuations can be just as damaging.

Other investigators (2) have obtained good mechanical properties in filament wound structures with larger-than-standard diameter round filaments. A simple analysis showed that larger microtape filaments could be placed into a tighter overall structure; that is, one with a lower percentage resin gap from edge-to-edge while still requiring less critical dimensional tolerances.

Various larger microtape filaments were drawn and a filament about 0.0015" thick and 0.060" wide was chosen as a size that could be made consistently to close dimensional tolerances with a good flat cross sectional shape and with sufficient strength to wind without breaking at the guides nor at the relatively small diameter mandrel. This larger filament would require only about 1-1/2 miles of microtape to make the same size specimen. The specimen could have an improved structure even though the filament width tolerance was relaxed to ±0.001" since the precision winder tolerances remain the same for any size filament.

A collection of some of the 2.6" I.D. tubes is shown in Figure 5. A few of the 5-3/4" I.D. tubes wound with solid 0.020" wide microtape are shown in Figure 6. Some unusual properties of microtape hoops are illustrated in Figures 7 and 8. When the flat filaments are thoroughly wet by the resin, the structure has amazing transparency. Figure 8 illustrates the spring characteristics of microtape hoops with their laminar structure and high glass content.

Filaments with Other Cross Sections

While most of the precision wound structures were made from solid microtape, other filament shapes that were wound into structures include two different hollow microtapes; one with rectangular holes drawn from two sheets of window glass separated by five bridges, the other drawn from seven soda-lime glass tubes cemented together. Cylindrical structures were also wound from hollow hexagonal filaments.

Dimensional control of the width of hollow microtape proved to be more difficult than it was with solid microtape. Probably there is more interaction between the thickness and the width of a hollow structure while solid microtape is a more simple solid, not much more than a two dimensional tape. Cross sections through structures made from each of the types of hollow microtape are shown in Figures 9 and 10.

In the precision winding of hexagonal filament, several new problems must be dealt with. Each layer must be wound in the same direction; in

order that the filaments can intermesh properly, every layer must be a helix wound in the same direction as the first layer. For example, using screw thread parlance, all the unidirectionally wound tubes have been produced in the direction of left-hand threads, which was more convenient to do on the equipment located here.

In a hexagonal filament wound structure, the first layer establishes the spacing for the whole structure. Stated another way, the first layer must be the proper "threads per inch" to match the flat-to-flat size of the filament in order to produce a perfect micro-honeycomb. Figure 11 is a photomicrograph of a cross section through the wall of a tube wound from hollow hexagonal filament. While this wall has a very regular structure with uniform filament size, it is evident that the first layer with its flats against the mandrel established too wide a spacing, with too few threads per inch to force the subsequent layers to wind with their vertical sides virtually touching one another. In this specimen, the same size filament was used in the first layer which positions itself flats down as was wound in subsequent layers. The first layer, even if its points were touching, would have established too wide a spacing for the following layers of the same size filament. Future work on this problem should use a smaller hexagonal filament in the first layer or a round filament whose size is chosen to provide proper spacing for the remainder of the tube.

During the first year's effort on shaped fibers, no great quantity of any one shape was required. Therefore, preforms for various shaped solid filaments could be ground out of a larger piece of glass by hand to make a long enough preform to prove the technique. Hollow fibers, on the other hand, can usually be made from a preform cemented together or even from one or more tubes of glass.

This year, when it was requested that we ship a given quantity of several different fiber shapes to other NASA contractors, it was decided that some work should be done on prefusing glass together to make solid preforms whose cross sectional shape would be suitable to make such solid fibers as an ellipse and a rhombus. A technique that gave moderately good results was that of building up long bars from long thin sheets of glass of the proper width to approximate the desired cross section. These strips are stacked flat in a furnace and fused together after which the bar is annealed. The preforms then look like the illustrations in the calculus to show integration. The small discrete steps on the surfaces virtually disappear upon drawing the fiber from the built-up prefused preforms.

It was during the making of shaped fibers of specified cross section and size that the problem of maintaining size over long lengths had to be solved. The forming of shaped fibers had been mastered during NASw-672. However, maintaining constant dimensions over a long length required optimizing the drawing conditions such as temperature and temperature gradient

in the furnace and keeping to an absolute minimum any draft from the chimney effect up through the drawing chamber.

Shipment of shaped fibers was only moderately successful. Immediately after forming, the fibers were coated with paraffin dissolved in heptane in order to protect them in shipment. This expedient had been successful in making an earlier small commercial shipment of coarse solid round glass fiber. The shaped fibers were wound onto tubes made from thick plastic sheet. By warming the tubes of glass before unwinding, the paraffin can be softened. Then the paraffin can be burned off so a clean filament is ready to accept a coupling agent and resin. Unfortunately, the filament tended to shift on some of the tubes during shipment and was difficult to unwind with some breakage having occurred.

Early in our attempts to precision wind shaped filaments, it was found that direct winding while forming was far more satisfactory than winding the filament onto a spool and subsequently unwinding it when making it into a structure. Tension control on single filaments with a tensioning device is very difficult. During forming, on the other hand, the viscosity of the glass and the guides provide a reasonable, very constant tension. Another disadvantage to winding in a separate operation from forming is that many of the shaped filaments have flat surfaces which tend to stick together making unwinding very difficult.

Shaped Fibers from Polymers and Fused Silica

During the course of performing Contract NASW-1100, applications for the preform attenuation technique were extended into both high and lower temperature materials. In a small part of the program, filaments were drawn successfully from styrene, polyvinyl chloride, nylon and polypropylene. Not only were solid and hollow round filaments made but in some cases, odd shaped fibers were made.

A few successful drawing experiments were also made with fused silica rods and tubes. It was found that by drawing a vacuum on a silica tubular preform, a fiber with a dumbbell-shaped cross section could be formed from fused silica.

Properties of Structures Wound from Shaped Fibers

The largest amount of data was developed on 2-3/8" diameter thin-wall tubes wound from solid microtape. This specimen was chosen to minimize end and edge effects in a specimen that was appropriate to make by precision filament winding with microtape.

Specimen Design:

In spite of the large overlap in the width direction of microtape in a circumferentially wound tube, internal pressure burst tests with unrestrained ends showed that the axial strength was low and the clean breaks around a circumference were evidence of axial failures.

In order to achieve even better filament placement than had been possible with the 0.020" wide by 0.0005" thick microtape, the larger tape was used - 0.060" wide by 0.0015" thick. Tubes 30" long were wound and these were cut into two or three equal lengths for testing.

In an effort to make a more balanced structure, some axial layers of microtape were incorporated in a few tubes. Although the failures were more ragged indicating a more nearly biaxial stress field, the results were no better possibly due to the use of an improper resin system and the fact that these trial tubes were too thin, having only a 0.0153" wall compared with most of the tube test specimens with a 0.034" to 0.040" wall.

These cross wound tubes were made by first winding single layers of resin-wet microtape onto a plastic film transfer sheet on a large 9" diameter mandrel. A number of these single layers were cut off the mandrel and set aside. Then with the 2.3" diameter mandrel on the winder, after four circumferential layers had been applied, the machine was stopped while two single layers which had been made earlier on the 9" mandrel were carefully wrapped on top of the hoop winds with the microtape running in an axial direction. Finally, four more circumferential layers were wound on top to complete the structure.

Test Method:

Most of the tubes were tested by filling them with water and applying an internal pressure to them, pressurizing the water with compressed

nitrogen. Steel caps were cemented to each end of the test section with an inlet in one of them for pressurizing.

The thickness shown has been measured through a microscope after the test was completed on a polished cross section cut from the wall of the tube near the point of failure. The measurement is made from the inside of the inner microtape layer to the outside of the outer glass layer. It includes all the glass and the interlaminar resin layers but it excludes the excess resin layer on the exterior surface of the tube as well as any that may be present on the inside.

The tube tests have been for the most part what is called "step burst" tests where the pressure is raised 100 psi and held for a minute after which readings are taken and the cycle is repeated; raise 100 psi, hold one minute, then read. Procedures other than this are noted under the "Type Test" column.

The water pressures were read using various range Bourdon Tube pressure gauges. The maximum stress was calculated on the basis of the maximum pressure and the dimensions of the tube.

In order to obtain modulus data, flat wire ribbons were spring loaded circumferentially and axially on the outside surface. A reference mark was scribed on adjacent ribbons and the position of the reference marks was read

with a 6-power comparator to 0.001". These then generated stress-strain data for computing modulus.

All the tubes were pressurized with both ends free to move with respect to one another, except the first one which was first tested with the ends held together with tie bolts.

Discussion of Test Results:

Table I contains the data on the construction of the tubes as well as the test results. The first portion of the table, I-A, describes the construction of the tubes and the type of test that was applied while the second part, I-B, shows the results of the test.

Ten different resin systems were used in an effort to find a system that would perform better in the microtape structure with its thin, approximately 1/2 micron, resin layers. It can be seen that the number of layers of microtape is approximately proportional to the thickness, which is expected.

As will be noted, failure did not occur on the first test up to 1500 psi internal pressure while the ends were restrained although there was noticeable cracking. It was only after the ends were free to move because the tie rods were removed that the tube burst. The lower modulus figures on the second test of this tube may be attributed to the resin cracking under the first pressurizing making the tube act softer upon retest.

The quick burst test gave the highest maximum stress. Since all the failures with the unrestrained tests appeared to be axial failures with fairly clean breaks, the circumferential maximum stress values are only of interest to see what levels were reached before failure occurred in the axial direction.

The modest stress levels at which failure has occurred has been interpreted as meaning that the proper resin system for the exceedingly thin, large area resin layers has not been found. The requirements for a suitable resin could approach the properties proposed in the following hypothetical resin specification:

Requirements:

High elongation	>200, prefer >500%
Low cure shrinkage	<3%
High tensile strength	12,000+ psi
High shear strength	10,000+ psi

Long pot life
Viscosity of about 500 centipoises
Solventless system
Absolutely no volatiles during curing

The most striking feature of the test results is the unusually high modulus of elasticity demonstrated by the high glass content tubes. Soda-lime sheet glass with a modulus of elasticity of 10.0×10^6 psi was used as a preform stock from which the microtape was drawn. The resins have a modulus of less than 1×10^6. Instead of the material yielding values on the basis of mixtures, the resin seems to have lost any effect it might have on this structure to lower the modulus.

The reason for the spread of the modulus values is difficult to comprehend. The measurements were all made using the same direct reading technique. The results were all calculated very carefully using a graphical method or a least-squares analysis, and in some cases both. Since some circumferential values are higher than their axial counterparts and vice versa, no pattern exists here; nor do they seem to be at all related to the resin systems.

It should be borne in mind that these elastic modulus values, as observed, are in a biaxial stress field. Using the effects of Poisson's ratio on parallel fibers in a biaxial field, such as the analysis in Appendix A, the moduli would convert to 6.2×10^6 psi for a unidirectional tensile modulus in the axial direction and 8.8×10^6 psi in the hoop direction. These values are remarkably high compared to the lower values exhibited by normal filament wound composites, which behave the way one would expect mixtures to behave.

Some of the same single layers of solid microtape were also made into flat laminates. A flat laminate was also made from layers of hollow microtape. The solid microtape laminate was tested in flexure and displayed the same high modulus of elasticity in both directions that has been measured in the tubular specimens. Such high moduli are not found in ordinary glass fiber reinforced plastic laminates. Some so-called unidirectional fabric laminates have relatively high modulus but only in one direction.

A preliminary investigation into the torsional behavior of two 2-3/8" tubular samples was also undertaken. The table below compares shaped filament wound tubes with a test run on a steel tube of similar size as a control.

	Wall Thickness	Torsional Modulus psi x 10^6	Maximum Stress at Failure, psi x 10^3
Steel	.035	8.3	-
12/9 A	.022	2.7	19.2
12/9 B	.034	2.3	23.3

It would appear that microtape wound tubes could perform well as lightweight torque tubes.

When some preliminary 2.6" diameter tubes were wound with the smaller microtape, 0.0005" x 0.020", some short 1" lengths of the tube were tested in axial compression. The deflections were recorded in order that an indication of the compressive axial modulus could be estimated. The results are tabulated as follows:

	Thickness, in.	Compressive Modulus x 10^6 psi		Compressive Strength, psi x 10^3
		0-2000#	0-10,000#	
8/12-1	0.029	4.0	3.3	12.9
-2		3.6	2.9	17.0
-3		4.4	4.3	29.0
8/12A-1	0.039	7.8	4.5	>30.8
-2		4.5	5.6	>30.8
9/17-1	0.046	2.8	4.0	25.2
-2		4.8	4.2	>24.8
-3		4.4	5.2	>24.0
9/21-1	0.034	5.9	5.0	33.2
-2		5.1	4.3	34.3
-3		5.0	5.1	26.9
8/6-1	0.039	-	3.3	19.5
-2		4.8	3.4	19.1
	Average	4.5		

Although care was taken to grind the ends of the test specimens flat and load them with flat, hard platens, there were indications by the types of failures and the level and spread of the values that the ends of the specimens were affecting the results. The modulus data can be only approximate since with the short sample, deflections must be measured very accurately and, in the particular arrangement used, a large correction factor had to be applied for apparatus distortion. Since this is a unidirectional field, these results should be compared with the internal pressure results adjusted for Poisson's ratio. This average of 4.5 x 10^6 psi should approximate the adjusted value of 6.2, indicating that these results are low.

One more burst test was run on a single 2-3/8" tube which was wound from hollow microtape made from seven glass tubes fused in a row. The resin system consisted of 60 phr Epon 826, 40 phr DER 736, 91 phr MNA with 0.3% BDMA and 2% Z-6040. Even though this microtape was so hollow that it made the structure light enough to float on water, the exterior shape of such a filament does not permit perfect packing and the tube was indeed resin rich. The test of this 0.043" wall thickness tube which failed at 175 psi calculates to a maximum stress of 2.4×10^3 psi axial and 4.8×10^3 psi hoop. The modulus figures show the effect of the resin richness and low glass content because of the very thin walls with 0.7×10^6 psi axial and 5.2×10^6 psi circumferential. The ratio of modulus to density is a most respectable 5.8×10^6 psi/gm/cc in the hoop direction.

About halfway through the year's effort some 5-3/4" diameter (NOL ring size) short tubes were made from solid microtape using a new developmental high elongation epoxy-like polyester resin alone and in blends with Shell's Epocryl E-11 and styrene. The series of tubes were made to evaluate the resins and check the shear strength of a microtape structure. To obtain definitive results, a much larger number of specimens would have to be made. Variations in the quality of the structure, such as the closeness of packing and the regularity of filament placement, appeared to overshadow the effects of the resin changes. Also, the consistency of the resin and its stability throughout a run affect to a large extent how accurately the

flat, thin filament can be placed. A summary of the shear strength results follows:

Developmental Resin with 20% Styrene:

Poor structure hoop	2,000 psi
Better structure hoop	5,660 psi

Developmental Resin with 50% Epocryl:

Good structure hoop	9,700 psi
Slightly thicker resin layers yielding slightly inferior packing	8,090 psi

In the same manner that some single plies of solid microtape were wound on a 9" diameter mandrel and then cross plied into a tube, two flat cross plied laminates were made. The laminates were bonded with Epon 828 resin hardened with MNA.

Flexural strengths and moduli, measured in both directions, are as follows:

Sample	Thickness, in.	Flexural Strength psi x 10^3	Flexural Modulus psi x 10^6
36 ply Laminate			
A	0.058	47.3	6.4
B	0.058	24.9	5.6
C	0.058	44.7	5.9
15 ply Laminate			
A	0.025	58.5	7.8
B	0.025	55.1	8.0
C	0.025	58.0	7.8

These results give further support to the high modulus values obtained on the 2-3/8'' diameter microtape wound tubes.

Some flexural modulus and density data were obtained on segments of 5-3/4'' diameter hoops made with four different filament shapes. These were tested in flexure both convex up and convex down. Since one of the broad objectives of the program is high stiffness-to-weight structures, ratio of modulus to density is also shown in the table below:

Tube	Fiber Shape	Ef* Convex Up psi x 10^6	Ef* Convex Down psi x 10^6	Ef* Average psi x 10^6	Density of Composite gm/cc	Ratio Modulus of Elasticity to Density psi/gm/cc x 10^6
10/8/65	Hollow Hex	3.04	2.80	2.9	1.03	2.82
11/15/65	Solid Micro-tape	6.00	8.4	7.2	2.17	3.32
1/4/66	Rect. Hollow Tape	3.32	2.88	3.1	1.35	2.30
1/6/66	Tube Hollow Tape	1.62	1.67	1.64	1.01	1.62

* Ef - Flexural Modulus of Elasticity

The hollow hexagonal hoop is the one shown in Figure 11. If the resin between adjacent filaments were eliminated through closer axial packing, the density would drop to about .98 with a filament whose wall thickness and size was the same and it would be expected that the modulus might increase to approximately 8.0 x 10^6 psi with thin resin joints in all directions. In a

similar way, better packing of the hollow microtape filaments should increase their moduli substantially. This should be readily done with the rectangular hollow microtape filament when the technique for forming it to constant size is further refined. The data on the solid microtape tube, included here as a control, further substantiates the high modulus it is possible to obtain with a well-packed shaped fiber.

CONCLUSIONS

The precision winding of several different cross section glass fibers was carried out fairly successfully.

High glass content structures can be made from microtape, a continuous glass filament with a high aspect ratio, 40:1, rectangular cross section. Such structures exhibit a modulus of elasticity approaching that of the glass itself.

Similar structures can be made from hollow microtape, combining the benefits of high modulus with low density in a structure.

A precision wound "micro-honeycomb" can be made with hollow, hexagonal glass filament. This structure also has a high stiffness-to-weight ratio.

The difficult task of precision forming and winding requires still further refinement to take full advantage of the close packing possible with shaped filaments.

The test results indicate that the resin systems studied are inadequate for bonding shaped filaments. The thin, 1/4 micron, layers of large area appear to require a high elongation, high strength resin. The resin requirement is more one of an adhesive than a casting resin.

In addition to soda-lime, borosilicate, lead and E-glass, it is possible to form shaped filaments from a number of organic polymers at lower temperatures and fused silica at higher temperatures by the preform attenuation method.

Recommendations for Future Work

In order to take the fullest advantage of shaped fibers, a resin should be developed that will perform well with shaped fibers. The thin, flat resin layers which exist between the flat surfaces of precision wound shaped filaments appear to require a different resin system. This resin needs a balance of properties not presently available in the systems commonly used for bonding glass fibers for structural purposes.

In view of the advances that have been made in precision winding of shaped glass fibers, a program should be undertaken to further refine the process so all the properties of shaped fibers can be utilized.

The lathe precision winder should be modified to make the traverse mechanism operate in perfect synchronization with the winding mandrel drive. The capabilities for monotonic winding should be further improved

so that traversing and winding will be at truly constant speed.

When the further process refinements have been made and a proper resin system has been developed, a more definitive study should be made of the properties of shaped filament wound structures taking advantage of the improved state-of-the-art of forming and winding.

The possible improvements over microtape windings in shear strength should be investigated for hexagonal filament structures and fibers of a corrugated nature.

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TABLE I

Internal Pressure Tests - 2-3/8" Diameter Microtape Tubes

I-A - Construction and Type of Test

Tube Designation	Resin System (Table II)	Layers of Microtape	Thickness, in.	Type Test
10-21 R	1	19	0.038	Step, restrained end, no burst
10-21 R	1	19	0.038	Same specimen, step burst
10-20	2	17	0.034	Step
10-26 L	3	22	0.037	Step
10-26 R	3	22	0.037	Quick burst, 0.78 min.
10-27 R	3	22	0.037	Step
11-5 R	3a	19	0.034	Step
11-5 L	3a	19	0.034	Fatigue
11-8 L	1	21	0.040	Step
11-9 L	4	22	0.035	Fatigue
11-9 R	4	22	0.035	Step
11-11 R	5	19	0.034	Step
11-19 L	6	22	0.034	Step
11-26 L (1)	6	11	0.019	Step
11-30 L (1)	7	12	0.019	Step
12-6 B	7	24	0.038	Step
12-16	8	22	0.036	Step
12-17 BR	9	22	0.034	Tested twice, step 1st test to 1,000 psi
12-22 AL(1, 2)	10	Note 2	0.015	100# step
12-22 AR(1, 2)	10	" "	0.015	50# step

Notes: (1) Tapered transition wound onto ends of thin test specimens

(2) Ten layers - 2 axial layers between 4 inner and 4 outer circumferential layers

TABLE I

Internal Pressure Tests - 2-3/8" Diameter Microtape Tubes

I-B - Test Results

Tube Designation	Maximum Pressure, Water psi	Maximum Stress, 10^3 psi		Elastic Modulus, 10^6 psi	
		Axial	Circumferential	Axial	Circumferential
10-21 R	1500	None	42.7 no burst	None	9.5
10-21 R	1100	15.7	31.3	6.7	8.6
10-20	1100	18.8	37.6	8.6	9.8
10-26 L	1100	17.0	33.9	10.6	10.0
10-26 R	1550	24.5	49.0	-	-
10-27 R	250*				
11-5 R	900	15.5	31.0	-	10.3
11-5 L	600	10.3	20.6	13.3	10.4
11-8 L	1125	16.6	33.2	11.8	14.2
11-9 L	600	9.9	19.8	8.9	11.2
11-9 R	1100	18.2	36.4	13.5	11.4
11-11 R	800	13.7	27.4	10.2	16.0
11-19 L	1100	18.6	37.2	9.3	11.5
11-26 L	600	19.0	38.0	10.5	10.3
11-30 L	600	18.4	36.8	10.4	8.9
12-6 B	880**	13.6**	27.2**	14.2	10.1
12-16	1270	20.8	41.5	11.9	9.3
12-17 BR	1270	21.4	42.7	14.2	11.8
12-22 AL	450	17.0	34.0	-	-
12-22 AR	480	18.2	36.4	10.9	12.1
		Average step burst tests		Average omitting repeat on 10-21 R	
		17.8	35.6	11.3	11.2

* poor structure

** not maximum stress, cap failure

TABLE II

Resin System Formulations

No.	
1	Epon 826 - 60 phr, DER 736 - 40 phr, HHPA - 81 phr, BDMA - 0.3%, Z-6040 - 2%
2	ERL 2256 - 100 phr, Sonite 41* - 27 phr, Z-6040 - 2%
3	Proprietary developmental epoxy-polyester resin
3a	Modification of "3" with increased catalyst and promoter
4	Proprietary developmental epoxy-polyester resin with styrene
5	DER 736 - 60 phr, Epon 826 - 40 phr, HHPA - 81 phr, BDMA - 0.3%, Z-6040 - 2%
6	Epon 826 - 80 phr, Epon 1001 - 20 phr, Tonox** - 25 phr, Z-6040 - 2%
7	Epon 826 - 80 phr, Epon 1001 - 20 phr, Tonox - 20 phr, MPDA - 5 phr, Z-6040 - 2%
8	Epon 826 - 80 phr, Epon 1001 - 20 phr, Tonox - 30 phr, MPDA - 7.5 phr, Z-6040 - 2%
9	Epon 826 - 80 phr, Epon 1001 - 20 phr, Tonox - 38 phr, MPDA - 9.5 phr, Z-6040 - 2%
10	Epon 826 - 100 phr, MNA - 91 phr, BDMA - 0.3%, Z-6040 - 2%

* Sonite 41 - Smooth-On Manufacturing Co.

** Tonox - Naugatuck Chemical, Div. of U.S. Rubber Co.

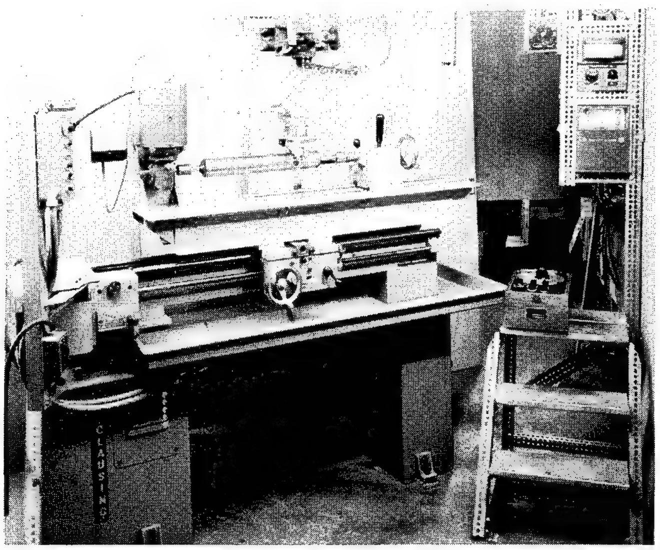


Fig. 1 - View of Lathe Winder Operator's Position

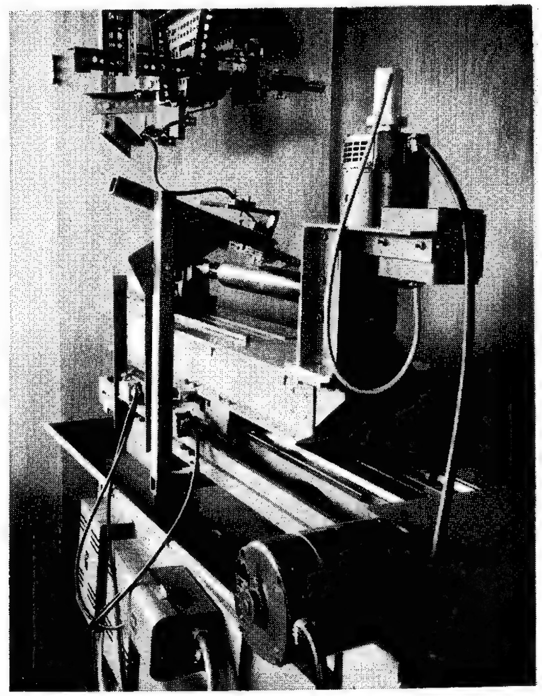


Fig. 2 - Rear View of Lathe Winder

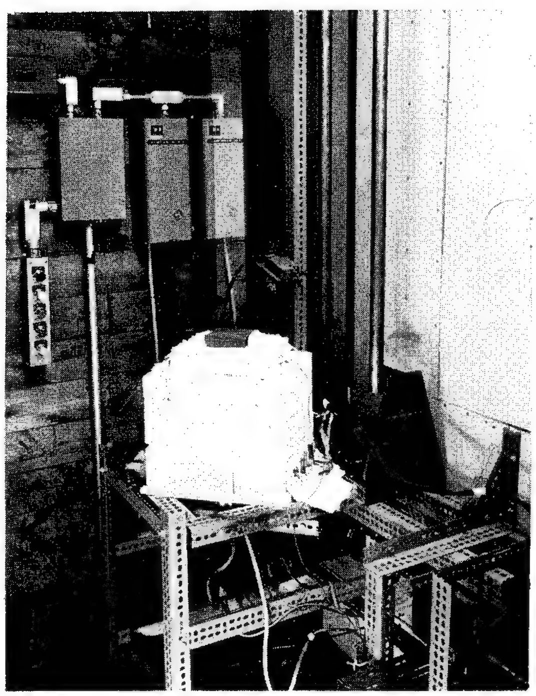


Fig. 3 - Side View of Furnace and Feeder on Second Level

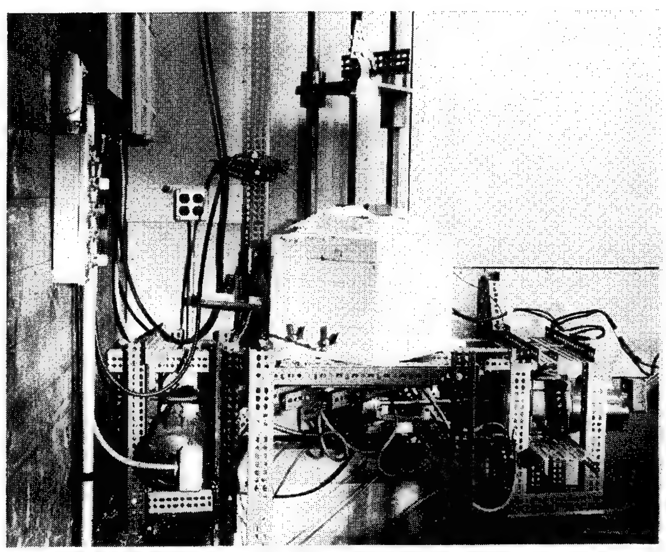


Fig. 4 - Front View of Furnace with Feeder Motors

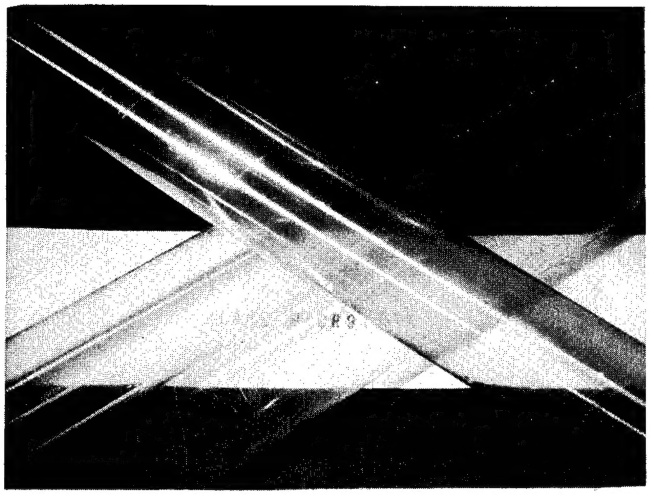


Fig. 5 - Lathe Wound Tubes

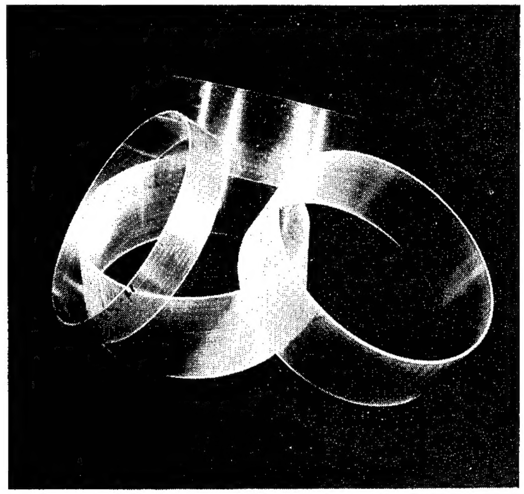


Fig. 6 - Microtape Hoops

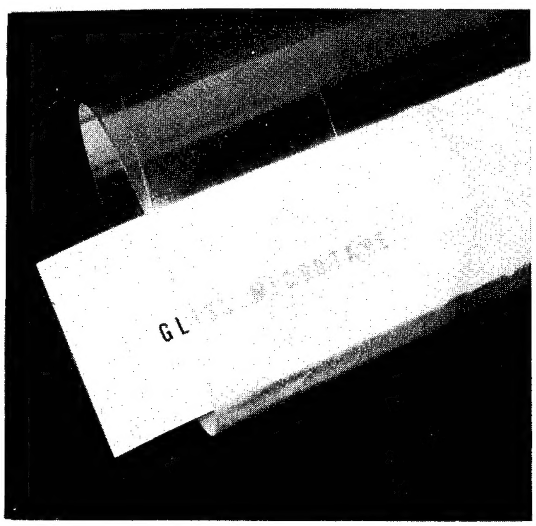


Fig. 7 - Transparent Hoop

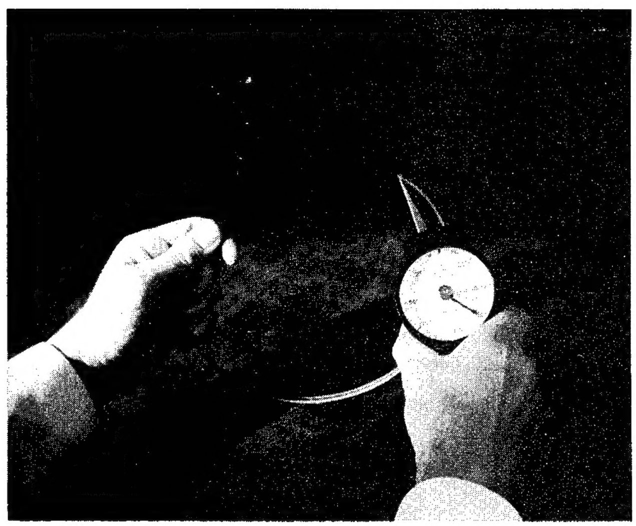


Fig. 8 - Microtape Spring

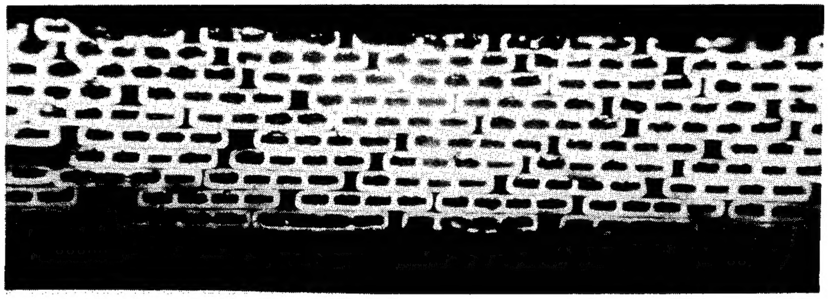


FIGURE 9 - Photomicrograph (50X) Showing Cross Section Through Hollow Rectangular Microtape

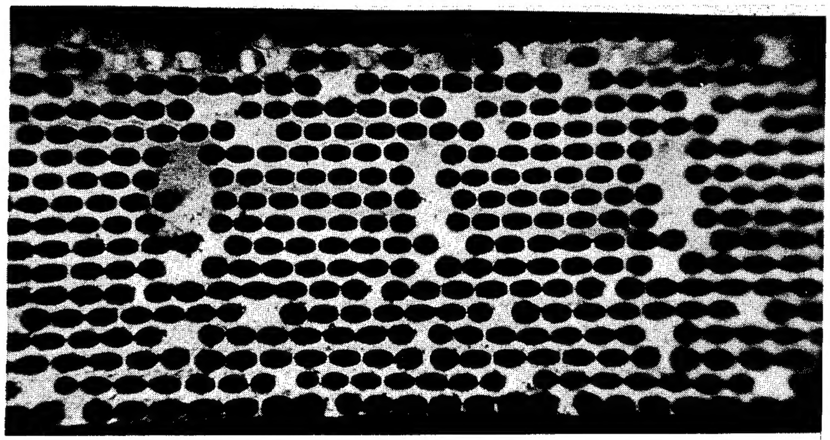


FIGURE 10 - Cross Section (50X) Through Hollow Microtape Made From Seven Tubes

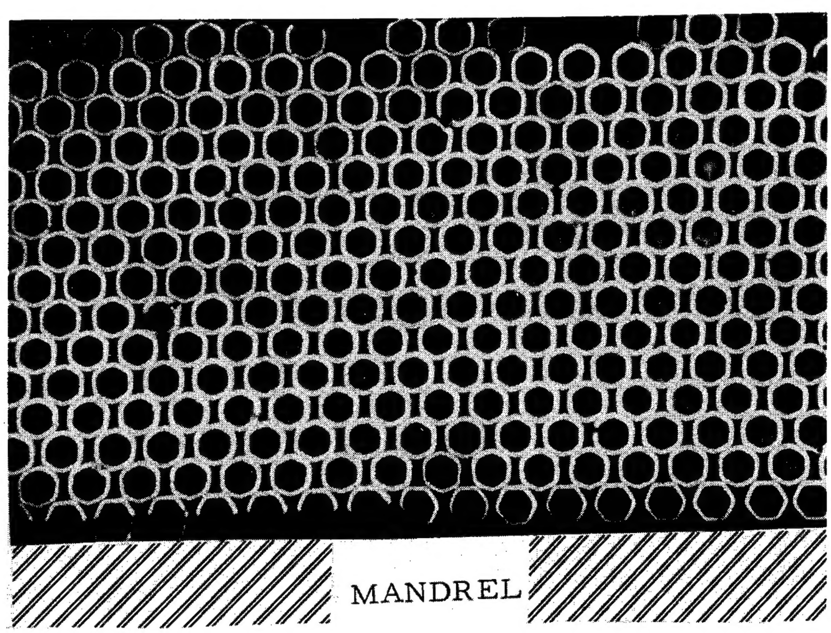
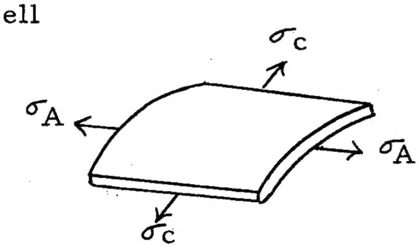


FIGURE 11 - Cross Section Through Hoop Wound From Hollow Hexagonal Filament. Note Flats-Down Layer Against Mandrel.

APPENDIX A

Analysis of the Poisson's Ratio Effect on a Thin Composite in a Biaxial Stress Field

by: Richard S. DeBell



In relating stresses and strains to arrive at a modulus, a tensile analogy is used, and an apparent modulus, E_a, is arrived at by dividing observed strains into the calculated stress:

$$E_a = \sigma / \sigma_a$$

In the general biaxial case, $l_1 = l_0(1 + \frac{\sigma_1}{E_1})(1 - \frac{\mu\sigma_2}{E_2})$ or approx. $l_0(1 + \frac{\sigma_1}{E_1} - \frac{\mu\sigma_2}{E_2})$

(1) hence, $E_A = \frac{\sigma_1}{E_1} - \frac{\mu\sigma_2}{E_2}$

For different materials cooperating in parallel to resist a load applied along the fibers, (sub-r = resin; sub-g = glass; sub-a = apparent)

$$\delta = \frac{Pl}{AE} = \frac{Pl}{A_{total}E_a} = \frac{P_r l}{.15A \cdot 1/3 \cdot 10^6} = \frac{P_g l}{.85A E_a}$$

$$P_r = P_g \cdot \frac{A_r}{A_g} \cdot \frac{E_r}{E_g} = P_g \frac{.15}{.85} \cdot \frac{1/3 \cdot 10^6}{10^7} = .0059\, P_g$$

$$E_a = \frac{(P_g + .0059\, P_g)\, l}{A\, \delta} = \frac{10^7}{1.0059} = \boxed{9,940,000 = E_c = E, \text{ circumferential}}$$

For different materials cooperating in parallel to resist a load applied perpendicular to the fibers,

$$\delta = \frac{Pl}{AE_a} = \frac{P \cdot .851}{AE_g} + \frac{P \cdot .151}{AE_r}\ ;\ \frac{.85}{10^7} + \frac{.15}{1/3 \cdot 10^6} = \frac{1}{E_a}\ ;\ E_a = .74 \times 10^7$$

$$E_a = \boxed{7,400,000 = E_A = E, \text{ axial}}$$

Returning to (1), the apparent axial modulus becomes (if $\sigma_c = 2\,\sigma_A$)

$$E_{Aa} = \frac{.5\sigma_c}{\frac{.5\sigma_c}{E_A} - \frac{\mu\sigma_c}{E_c}} = \frac{1}{\frac{1}{E_A} - \frac{2\mu}{E_c}} = \frac{10^6}{\frac{1}{7.4} - \frac{.6}{9.94}} = \boxed{13,500,000 = E_{Aa}}$$

and $$E_{ca} = \frac{\sigma_c}{\frac{\sigma_c}{E_c} - \frac{\mu\sigma_c \cdot .5}{E_A}} = \frac{1}{\frac{1}{E_c} - \frac{.5\mu}{E_A}} = \frac{10^6}{\frac{1}{9.94} - \frac{.15}{7.4}} = \boxed{12,450,000 = E_{ca}}$$

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